

# LOW FREQUENCY (11 MHZ) OSCILLATIONS IN H1743–322: A NEW CLASS OF BLACK HOLE QPOS ?

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## ABSTRACT

We report the discovery of quasi-periodic oscillations (QPO) at  $\sim 11$  mHz in two RXTE observations and one Chandra observation of the black hole candidate H1743–322. The QPO is observed only at the beginning of the 2010 and 2011 outbursts at similar hard color and intensity, suggestive of an accretion state dependence for the QPO. Although its frequency appears to be correlated with X-ray intensity on timescales of a day, in successive outbursts eight months apart we measure a QPO frequency that differs by less than  $\approx 2.2$  mHz while the intensity had changed significantly. We show that this  $\sim 11$  mHz QPO is different from the so-called Type-C QPOs seen in black holes and that the mechanisms that produce the two flavors of variability are most probably independent. After comparing this QPO with other variability phenomena seen in accreting black holes and neutron stars, we conclude that it best resembles the so-called “1 Hz” QPOs seen in dipping neutron star systems, although having a significantly lower (1-2 orders of magnitude) frequency. If confirmed, H1743–322 is the first black hole showing this type of variability. Given the unusual characteristics and the hard-state dependence of the  $\sim 11$  mHz QPO, we also speculate whether these oscillations could instead be related to the radio jets observed in H1743–322. A systematic search for this type of low-frequency QPOs in similar systems is needed to test this speculation. In any case, it remains unexplained why these QPOs have only been seen in the last two outbursts of H1743–322.

*Subject headings:* X-rays: binaries — binaries: close — stars: individual (H1743–322) — Black hole physics

## 1. INTRODUCTION

Quasi-periodic oscillations (QPOs) with characteristic frequencies between  $\sim 1$  mHz and hundreds of Hz have now been observed in the X-ray flux of many low-mass X-ray binaries (LMXBs) containing neutron stars (NSs) and black holes (BHs). The characteristics of many of these QPOs are known to generally correlate with the source spectral states and/or X-ray luminosity (see, e.g., van der Klis 2006, for a review).

A number of QPOs and broad band variability components can be present simultaneously in the power spectra of the X-ray light curves of accreting NS systems. These can be modeled with Lorentzian components and are often denoted by their characteristic frequencies (examples include the so-called break, the hump, the LF QPO, the *low* component and the upper and lower kilohertz QPOs, e.g., Altamirano et al. 2008a). Their frequencies are known to be correlated to each other (Wijnands & van der Klis 1999; Belloni et al. 2002). However, there are also components which appear to be uncorrelated. Among these uncorrelated exceptions are: (i) the hecto-Hz QPOs which have frequencies constrained within  $\sim 100$  Hz and  $\sim 300$  Hz (e.g., Altamirano et al. 2008a), (ii) the 1 Hz QPOs in dipping sources (e.g., Jonker et al. 1999, 2000; Homan et al. 2003), (iii) a QPO with frequencies in the mHz range which very likely results from marginally stable nuclear burning of hydrogen/helium on the NS surface (e.g., Heger et al. 2007) and (iv) the 1 Hz flaring observed in

two accreting millisecond X-ray pulsars when the sources were observed at low-luminosities (e.g. Wijnands 2004; Patruno et al. 2010).

BHs generally show three main types of low-frequency QPOs (Types A, B and C, e.g., Casella et al. 2005) and, in a few cases, high-frequency QPOs (with frequencies between 70 Hz and 450 Hz, e.g., van der Klis 2006, for a review). In some cases observed QPOs are not easily identified with either Type A, B or C; this may be due to having data of low statistical quality or a source being observed in an unusual spectral state. In general, some of the same variability components appear to be present in both NS and BHs (Miyamoto et al. 1993; van der Klis 1994; Belloni et al. 2002). For example, Casella et al. 2005 argue that the Type A, B and C QPOs in black holes correspond to the so-called Flaring Branch, Normal Branch and Horizontal Branch Oscillations, respectively, that were identified in high luminosity NS systems (the “Z” sources).

Outside of the Type A, B, and C QPO classifications there is additional low-frequency variability in BHs, including for example the “heart-beat” QPOs, observed so far only in the BHs GRS 1915+105 (e.g., Belloni et al. 2000) and IGR J17091–3624 (e.g., Altamirano et al. 2011).

Recently, Strohmayer (2011) reported on a *Rossi X-ray Timing Explorer* (RXTE) observation of the 2011 outburst of the black hole candidate (BHC) H1743–322. In addition to the typical Type-C QPO and strong broadband noise generally seen at the beginning of the outbursts of BH systems, Strohmayer (2011) found an unusual  $\sim 91$ s QPO which they suggested might be due to a second active source in the  $1^\circ$  Proportional Counter Array (PCA; Jahoda et al. 2006) field of view (FoV).

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However, subsequent observations with *Swift* and *INTEGRAL* did not show any additional nearby sources. Triggered by the possibility that this  $\sim 91$ s QPO might instead be intrinsic to H1743–322, we searched RXTE, Swift and *Chandra* data for other instances of similar QPOs. In this Letter we report the discovery of a similar QPO in additional RXTE and *Chandra* observations of H1743–322 and discuss the implications of our findings.

H1743–322 was first detected in outburst in 1977 (Kaluzienski & Holt 1977) and then rediscovered by *INTEGRAL* in 2003 (Revnivtsev et al. 2003). Since 2003 several smaller outbursts of H1743–322 have been observed (see Motta et al. 2010, and references therein). From its similarities with the dynamically confirmed BH X-ray binary XTE J1550–564, the source was classified as a BH candidate (McClintock et al. 2009, but also see Homan et al. 2005). H1743–22 is at a distance of  $8.5 \pm 0.8$  kpc (Steiner et al. 2011) and, from the evidence of X-ray dipping behavior in one observation (Homan et al. 2005), the inclination angle of its accretion disc is believed to be relatively high ( $> 70^\circ$ ) to our line of sight. However, this high inclination needs to be confirmed, as no thorough analysis of the dipping behavior has yet been reported.

## 2. OBSERVATIONS AND DATA ANALYSIS

The BHC H1743–322 was observed with the PCA onboard RXTE for a total of 558 pointed observations, sampling 9 different outbursts which occurred between March 2003 and June 2011. Some of the H1743–322 outbursts were also sampled with the Swift/XRT instrument (Barthelmy et al. 2005); we used all the 52 archival XRT observations to look for mHz QPOs. We also used a 60ks *Chandra* observation (id number, 401083), which was contemporaneous with RXTE observation 95368-01-01-00 (see Section 3). We extracted events from the 0th and 1st order High Energy Transmission Grating (HETG/ACIS-S) mode data with CIAO 4.3 following standard recipes<sup>3</sup>.

We used the 16s time-resolution PCA Standard 2 mode data to calculate X-ray colors following the procedure described in Altamirano et al. (2008a). We define hard color as the  $(16.0\text{--}20.0\text{ keV})/(2.0\text{--}6.0\text{ keV})$  count rate ratio and, intensity, as the count rate in the 2.0–20 keV band. All values have been normalized to the Crab Nebula on a per PCU basis and are presented here as averages per observation. In Figures 1 and 2 we show the light curves and hardness-intensity diagrams (HIDs) of the nine outbursts observed with RXTE.

We used 1-sec resolution PCA (2–60 keV; observed in Event, Good-Xenon and Single Bit modes) and Swift/XRT (0.5–10 keV) light curves to search for variability on timescales of a fraction of a minute or longer; this was done on a per orbit basis using Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 1992).

To study subsecond variability, we constructed Leahy-normalized power spectra per RXTE observation. No background or deadtime corrections were made prior to their calculation. We subtracted a predicted dead-time modified Poisson noise spectrum estimated from the power at frequencies higher than 1500 Hz, where neither intrinsic noise nor QPOs are known to be present, using

the method developed by Klein-Wolt (2004). The resulting power spectra were converted to squared fractional rms amplitude (van der Klis 1995).

## 3. RESULTS

We visually inspected each 1s light curve and each of the Lomb-Scargle periodograms from PCA data and consistently find clear evidence of mHz QPOs at  $\sim 11$  mHz in the two observations 95368-01-01-00 (MJD 55417.24, two orbits starting on August 9th, 2010 at 16:05 UT, averaged periodogram peaks at  $\sim 11.4$  mHz) and 96425-01-01-00 (MJD 55663.67, single orbit on April 12th, 2011 at 6:45 UT, averaged periodogram peaks at  $\sim 11.1$  mHz). The light curves are shown in Figures 3. For these two observations we calculated power spectra using 512s data segments. The left panels of Figure 4 show the clear  $\sim 11$  mHz peak in both cases. Their averaged quality factor  $Q$  is as high as  $\sim 100$  in the 2010 observation, but also as low as  $\sim 10$  in the 2011 observation. The average fractional rms amplitude in the 2–60 keV is  $3.1 \pm 0.4\%$ . Insets in Figure 4 show the 11 mHz QPO amplitude-energy dependence. In the 2010 observation the rms amplitude does not vary with energy, while in the 2011 observation it first increases and then shows evidence of a decrease with energy. However, the increase is only moderate ( $< 1\%$  rms) as compared with other QPO variability, which generally shows a more substantial increase with energy (e.g., Casella et al. 2004).

The power spectra in Figure 4 also show the typical Type-C QPOs on top of strong ( $\sim 30\%$  rms amplitude) broad band noise. Although the frequency of the mHz QPOs is similar in both observations, the frequency of the Type-C QPOs differs by a factor of  $\sim 2$ . We compared the overall power spectra produced using data from different phases of the 11 mHz QPO, but found no significant changes, implying that the mechanisms that produce the mHz and Type-C QPOs are not closely related.

Figure 1 and 2 show that the mHz QPOs were detected during observations at the beginning of the last two outbursts, i.e. of the 2010 and 2011 outbursts. These last two outbursts show very similar tracks in the HID, and the mHz QPOs appear at a very similar hard color. However, other observations at similar intensity and hard color do not show evidence of mHz QPOs. For comparison, the right panels of Figure 4 show the power spectra of the observations closest in the HID to those where we detected the mHz QPOs (marked with arrows in the inset of Figure 2).

Visual inspection of the Swift/XRT data revealed no evidence of mHz QPOs. No Swift–RXTE simultaneous observations are available when the mHz QPOs were detected. Swift observations occurred approximately two days before and five days after the 2010 RXTE detection of mHz QPOs, and only 5 days after the 2011 RXTE detection.

A *Chandra*/HETG observation started on August 8th, 2010, at 23hs UT and lasted until approximately 15hs 40min UT of the next day (i.e., until  $\sim 20$  min before the RXTE observation 95368-01-01-00 began). We extracted events both from the zeroth (undispersed) and dispersed orders and found in both cases a clear QPO at  $\sim 11$  mHz. In Figure 5 we show the dynamical power spectrum computed from the dispersed photons. The QPO frequency drifts upward with time and appears to be positively cor-

<sup>3</sup> <http://cxc.harvard.edu/ciao/threads/>

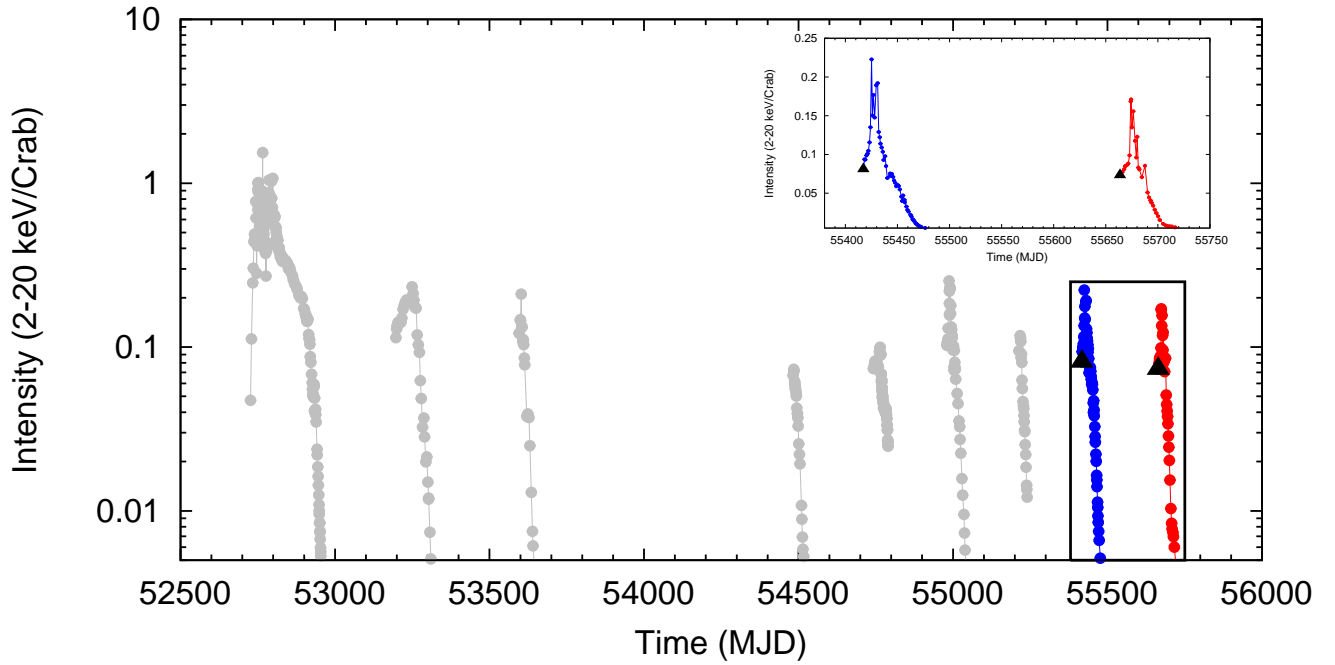


FIG. 1.— Crab-normalized light curves of all outbursts of the BHC H1743–322 as seen with RXTE pointed observations. Each point corresponds to an average per observation. The inset shows the last two outbursts. The triangles mark the times when we detected the mHz QPOs.

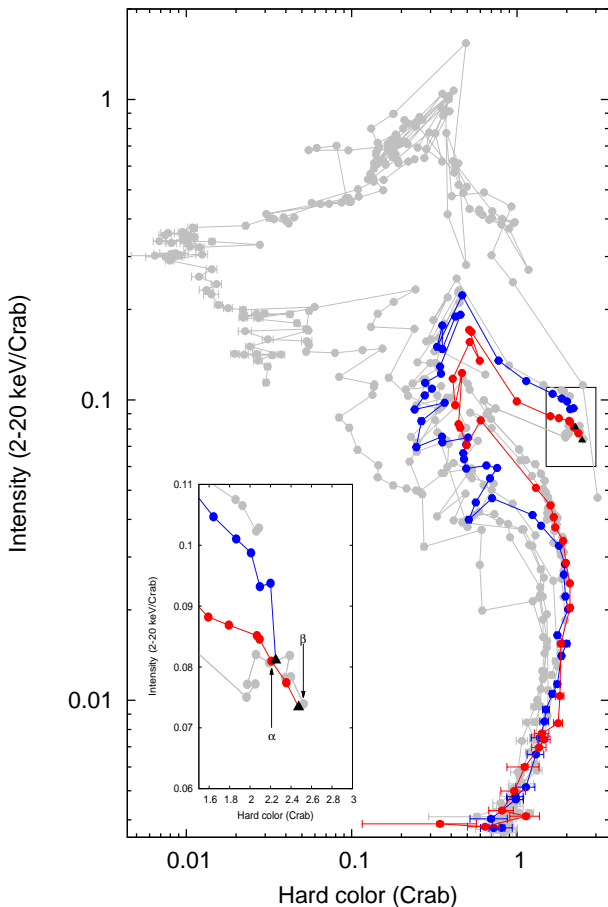


FIG. 2.— Hardness-intensity diagram of all outbursts of the BHC H1743–322 as seen with RXTE pointed observations. Each point corresponds to an average per observation. Inset: blow-up of the region in which we detected the mHz QPOs, with triangles denoting the mHz QPO observations. Arrows  $\alpha$  and  $\beta$  mark the comparison power spectra in Figure 4.

related with the intensity. The presence of the QPO signal in the zeroth order photons at a sky position consistent with the known position of H1743–322 confirms that the mHz QPO is intrinsic to this source, and not from a hitherto unidentified nearby source. A phase-resolved spectral analysis of these data is beyond the scope of this paper and will be reported elsewhere.

#### 4. DISCUSSION

We report the discovery of QPOs at  $\sim 11$  mHz in two RXTE and one Chandra observation of the BHC H1743–322. In successive outbursts eight months apart we measure a QPO frequency that differs by less than  $\approx 1.5$  mHz (including the 60ks duration of the *Chandra* observation, see Figure 5). The fractional rms amplitude of the oscillation appears to be correlated with energy in the 2011 observation, but consistent with a constant value in the 2010 observation. The QPO is observed at the beginning of two different outbursts at similar hard color and intensity, suggestive of an accretion state dependence for the QPO. Although the *Chandra* data reveal that the QPO frequency might be correlated with intensity on timescales of hours, this correlation probably changes in between outbursts, as we find the same frequency (within  $\approx 0.4$  mHz) in observations separated by about 800 days and at source intensities different by  $\approx 10$  mCrab (this resembles the so called “parallel tracks” observed in the frequency vs. intensity diagrams of NS kHz QPOs, e.g, Méndez et al. 1999). Except for the 11 mHz QPOs, the RXTE power spectra of these two observations are typical of the low-hard state of BH LMXBs, showing Type-C QPOs on top of strong broad band noise. Given that (i) the power spectra characteristics do not change with mHz QPO phase and (ii) the frequency of the mHz QPOs is rather constant ( $\lesssim 0.4$  mHz) between the 2010 and 2011 RXTE observation, while the Type-C QPO frequency varies by a factor of about 2, we conclude that mechanisms that produce the mHz QPOs and Type C QPOs

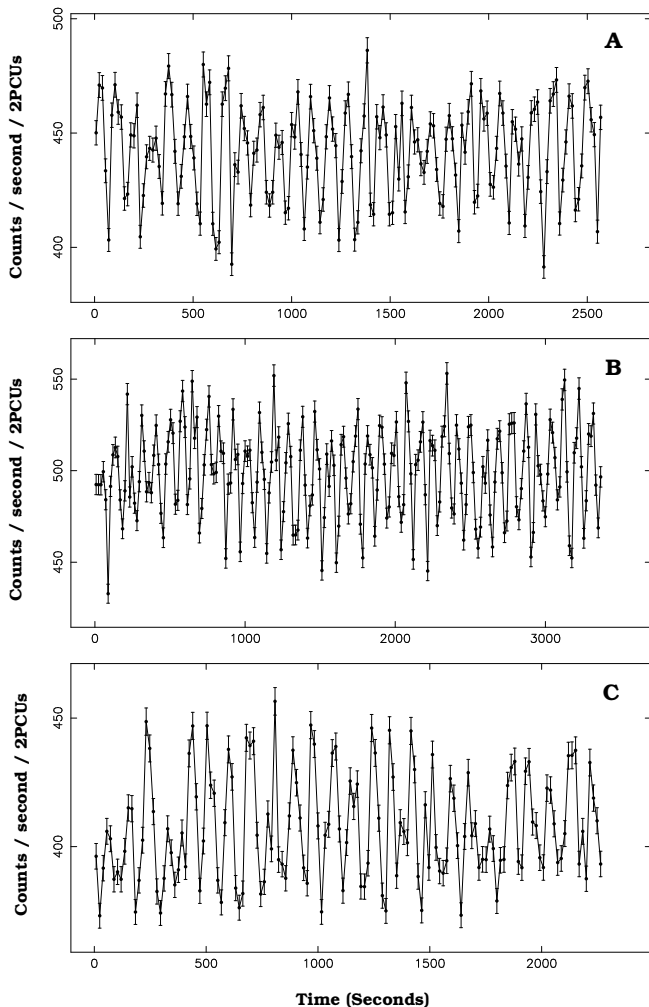


FIG. 3.— 10s binned RXTE light curves (2–60 keV) of the 3 orbits in which we detect the mHz QPOs. Panels A and B correspond to two orbits in observation 95368-01-01-00. Panel C corresponds to the single orbit observation 96425-01-01-00.

are not closely related.

The fact that the frequency of these new oscillations is fairly constant raises the question of whether they represent a characteristic frequency of a process not yet identified before. Several types of QPOs with frequencies in the mHz range have been reported in two BH systems and in some NS systems. Below we compare our results with those seen in other sources and discuss whether we can identify the 11 mHz QPOs with any of them based on the characteristics of the oscillations and the source state in which they occur.

Highly structured, high-amplitude variability has been seen in the BH systems GRS 1915+105 (e.g., Belloni et al. 2000) and IGR J17091–3624 (e.g., Altamirano et al. 2011). Some of these variations are known as “heartbeats” and are thought to be due to limit cycles of accretion and ejection in an unstable disk (e.g., Neilsen et al. 2011). These “heartbeat” QPOs are in the mHz range, occur only during the high-luminosity, soft-state of these two BH systems and, at least in the case of IGR J17091–3624, can have rms amplitudes as low as  $\sim 3\%$  (e.g., Altamirano et al. 2011). For H1743–322 we only find the new mHz QPOs during the rise of the outburst (at  $L_X < 3 \cdot 10^{37}$  ergs  $s^{-1}$ , e.g., Motta et al.

2010), when the spectrum of the source is dominated by the hard component. GRS 1915+105 is thought to be very often at an Eddington or a super-Eddington luminosity (e.g., Done et al. 2004); this could also be the case of IGR J17091–3624 although the distance to this source is not yet known (see discussion in Altamirano et al. 2011). Given the major differences between source state and luminosity in GRS 1915+105 and IGR J17091–3624 as compared with H1743–322, we conclude that the mHz QPOs in H1743–322 most probably represent a different phenomenon than the “heartbeat” QPOs and the other highly-structured low-frequency variability seen in GRS 1915+105 and IGR J17091–3624.

QPOs with intensity-independent frequencies in the mHz range have been found in at least four NS systems (Revnivtsev et al. 2001; Strohmayer & Smith 2011). The occurrence of these QPOs depends on source state, but they are thought to be the signature of marginally stable burning of helium on the NS surface (Heger et al. 2007). A similar QPO, but with an intensity-dependent frequency was also found in the 11 Hz X-ray pulsar IGR J17480–2446 in Terzan 5 (Linares et al. 2011). The fact that (i) the occurrence of these NS oscillations are intimately related with thermonuclear X-ray bursts, (ii) are thought to come from the NS surface and (iii) their spectrum is generally soft (Revnivtsev et al. 2001; Altamirano et al. 2008b), indicates that they are most probably a different phenomena from what we detect in H1743–322.

Wijnands (2004) reported a modulation at  $\sim 1$  Hz in the light curve of the accreting millisecond X-ray pulsar (AMXP) SAX J1808.4–3658. A similar type of QPO (Patruno et al. 2010) was found in the AMXP NGC 6440 X-2 (Altamirano et al. 2009). These QPOs have been seen at low luminosities (less than a few  $10^{36}$  erg  $s^{-1}$ ), at frequencies between 0.8 and 1.6 Hz and with large amplitudes (up to 100% fractional rms (Patruno et al. 2009)). The high amplitude of these oscillations, the fact that they have only been seen in AMXPs, and that their occurrence is most probably related to the onset of the propeller regime (Patruno et al. 2009) suggests that these  $\sim 1$  Hz QPOs are not related to those we see in H1743–322.

A so called “1 Hz QPO” has been reported for (four) dipping NS systems (Jonker et al. 1999, 2000; Homan et al. 2003; Bhattacharyya et al. 2006). These QPOs appear to be different from the “zoo” of correlated low-frequency features seen in the power spectra of NS systems. The fractional rms amplitude of these QPOs is approximately constant and energy independent during the persistent emission, dips and thermonuclear X-ray bursts. Although the QPO frequency has been seen to vary between 0.6 and 2.4 Hz in two of the sources (Jonker et al. 2000; Homan et al. 1999), the “1 Hz QPO” name stands for the fact that its frequency can be rather constant for long periods of time. It has been suggested that these QPOs are related only to high inclination sources from which we might be observing modulation effects of the accretion stream material falling onto the disk, or some kind of modulation produced at the disk edge (e.g., Jonker et al. 2000; Smale et al. 2001; van der Klis 2006, and references within). The fact that H1743–322 is thought to be a high inclination source (Homan et al. 2005), that the fractional rms amplitude

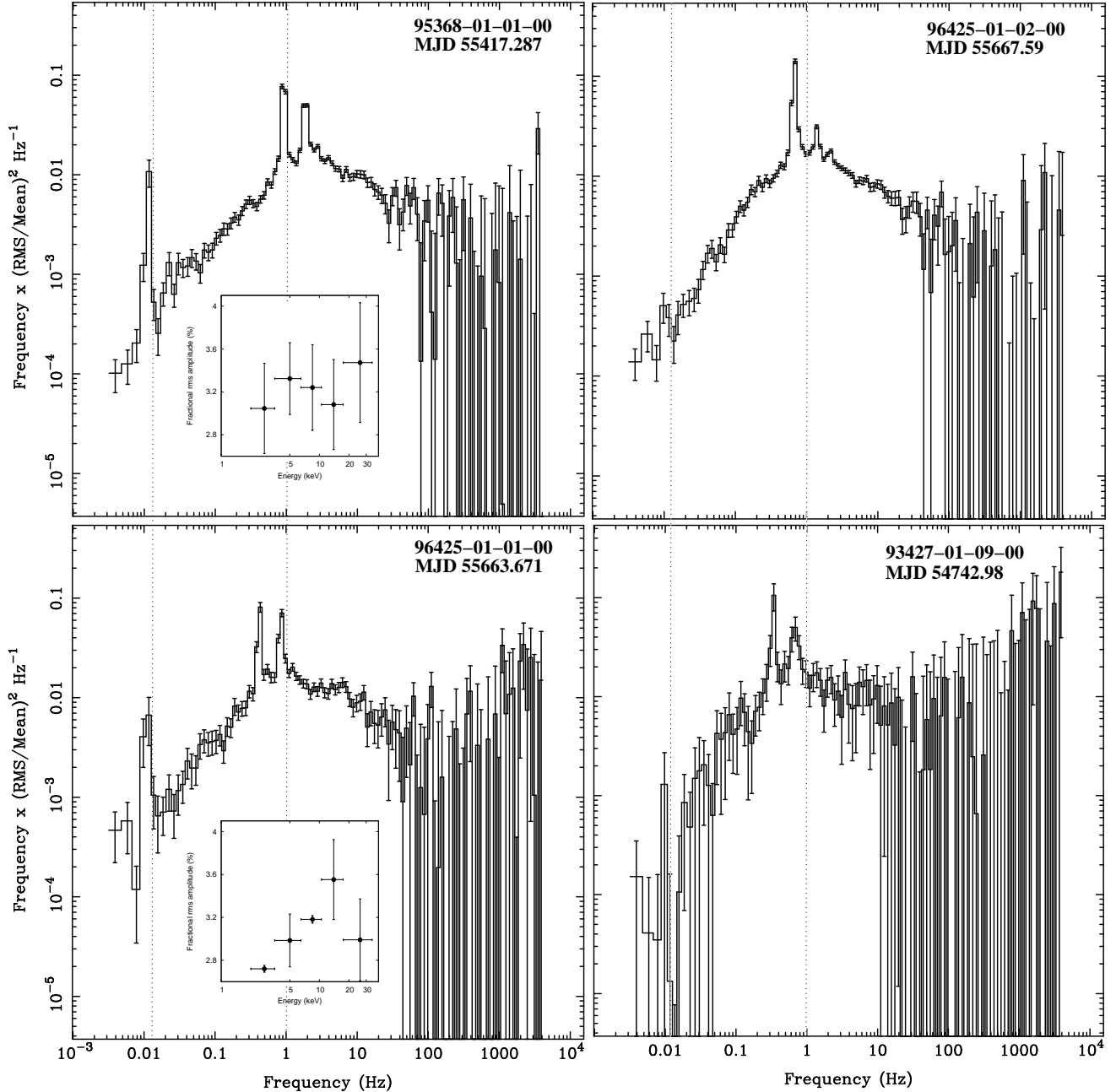


FIG. 4.— *Left*: Average power spectra of the two RXTE observations where we detect the mHz QPOs. In the upper panel (2010 observation) the Type-C QPOs are at  $0.919 \pm 0.001$  Hz and  $1.852 \pm 0.001$  Hz while in the lower panel (2011 observation) they are at  $0.424 \pm 0.003$  Hz and  $0.856 \pm 0.004$  Hz. Their quality factors (Q) are  $13.0 \pm 0.5$ ,  $10.0 \pm 0.6$ ,  $11 \pm 2$  and  $9 \pm 1$  and their fractional rms amplitudes  $11.9 \pm 0.2\%$ ,  $9.4 \pm 0.2\%$ ,  $10.7 \pm 0.4\%$ ,  $10.9 \pm 0.5\%$ , respectively. The inset panels show the fractional rms amplitude vs. energy for the 11 mHz QPOs. *Right*: Comparison power spectra without mHz QPOs but at similar spectral state (see Figure 2 and Section 3). The vertical dotted lines drawn at 12.5 mHz and 1 Hz are shown to guide the eye.

of the mHz QPOs we find does not vary strongly with energy and that its frequency is stable, indicate that they might be related to the process that produces the so called “1 Hz QPO” in dipping NS systems. If true, this would be the first BH system showing such QPOs, raising the question of why the frequency of the QPO is between one and two orders of magnitude lower in H1743–322 than in the NS. One possibility is that the frequency range in which this QPO occurs scales with mass or that it depends on the orbital period of the system, as H1743–322 is thought to have an orbital period longer than 10 hr (Jonker et al. 2010) while the NS systems have orbital periods shorter than 6 hr (e.g., Jonker et al.

1999, 2000; Homan et al. 2003). It is worth noting that the high inclination dipping BH 4U 1630–47 shows QPOs with frequency as low as  $\sim 0.1$  Hz, however, these QPOs are due to semi-regular short ( $\sim 5$  sec) dips (Dieters et al. 2000). Following Kuulkers et al. (1998) we produced colors using 1 sec light curves in different bands of the 2010 and 2011 observation of H1743–322. We do not observe any hardening (or any other variation) of the spectra as a function of QPO phase, implying that the 11 mHz QPOs are most probably not regular dips as seen in 4U 1630–47.

H1743–322 is well known for its radio jets (e.g., Steiner et al. 2011; Miller-Jones et al. 2012). Markoff et al. (2005) have suggested that the hard state

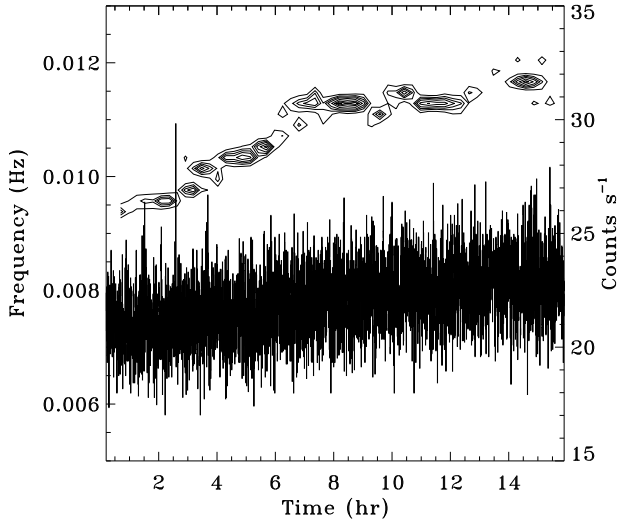


FIG. 5.— Dynamical power spectra from the dispersed (i.e., excluding the zeroth order image) HETG *Chandra* data showing the frequency evolution of the mHz QPO. We computed overlapping power spectra by using 5000 s intervals, with a new interval beginning every 1000 s. Contours of constant Leahy-normalized power are drawn at values of 25, 40, 50, 60, 75, 90, 100 and 110. Start time is August 8th, 2010, 23:03:48UT.

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emission could be due to synchrotron self-Compton emission from the base of the jet, and Russell et al. (2010) have recently suggested that the jet mechanism might have dominated the X-ray variability in a portion of the hard state of the 2000 outburst of the BHC XTE J1550–556. The 11 mHz QPOs we find in H1743–322 appear to be different from most types of variability seen in other BH and NS systems, and so we speculate whether these oscillations could be related to the radio jets observed in H1743–322. Unfortunately no radio measurements have been reported as yet for the 2010 and 2011 outbursts of H1743–322 (and the radio flux is known to change between outbursts, Miller-Jones et al. 2012) and to our knowledge no model yet predicts that the jet could sometimes modulate the X-ray flux at a characteristic frequency. Clearly more theoretical work is needed in this direction. If related to the jets, it remains unexplained why these low-frequency QPOs have not yet been identified in other BHs with known radio emission. Clearly, a systematic search for this type of low-frequency QPO in the RXTE BH archive is needed to test this speculation.